Challenges in Developing Hydrogen Supply Chains

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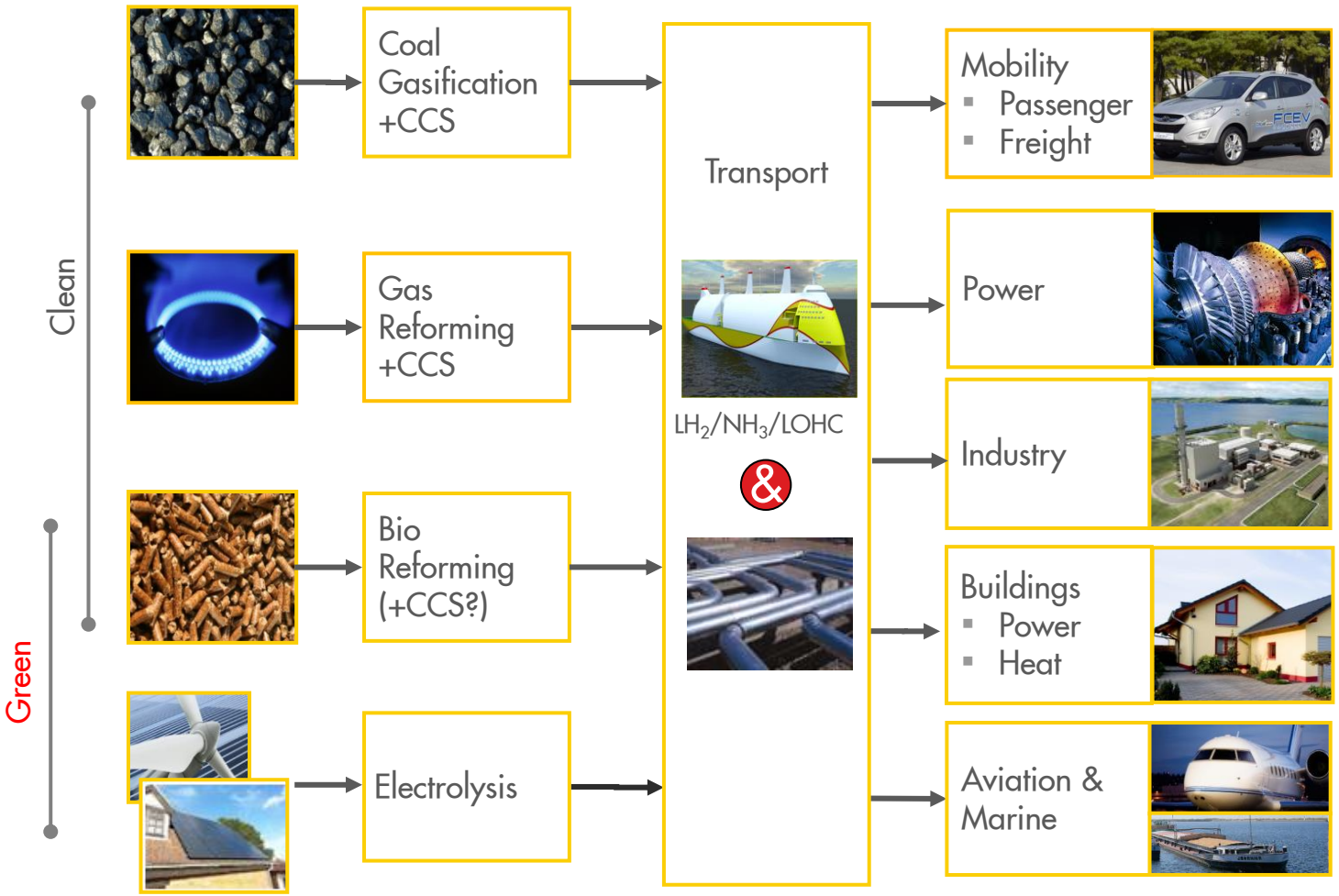
HYDROGEN SUPPLY CHAINS and MARKETS

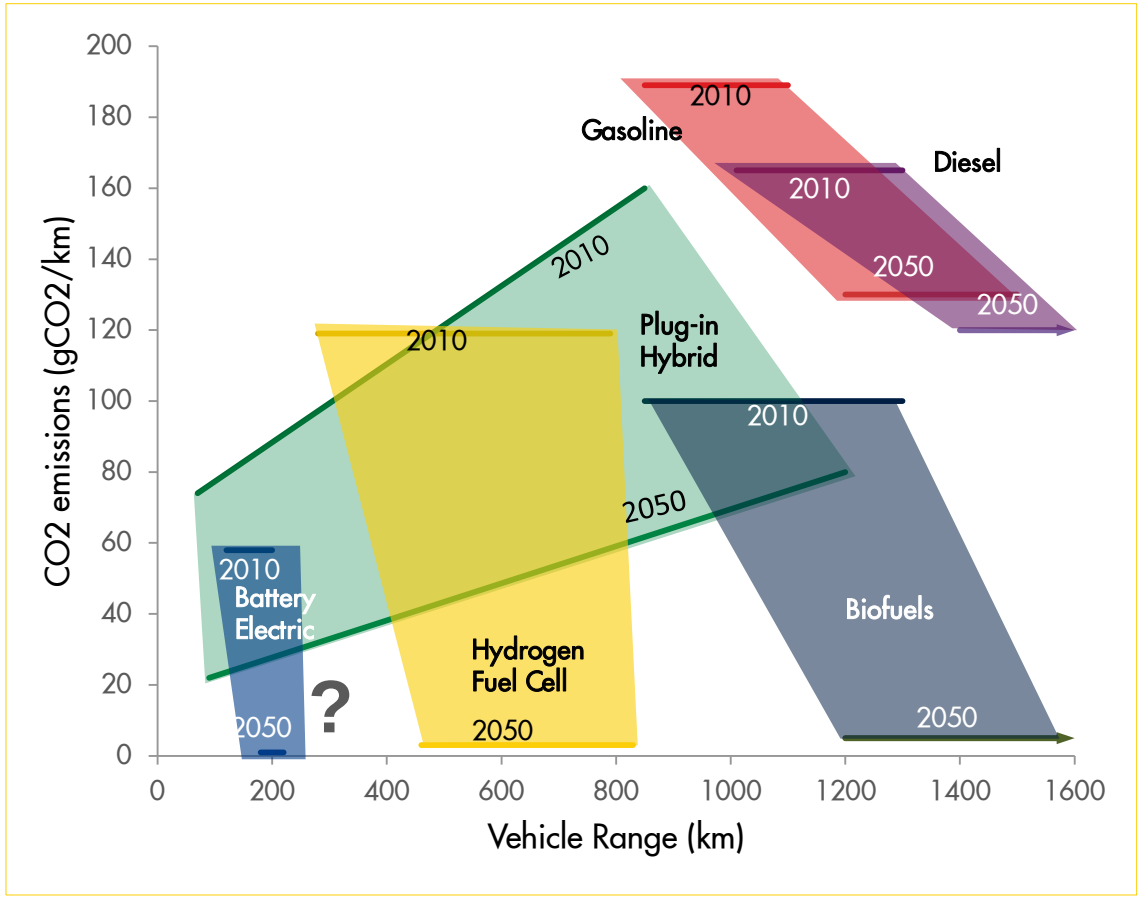


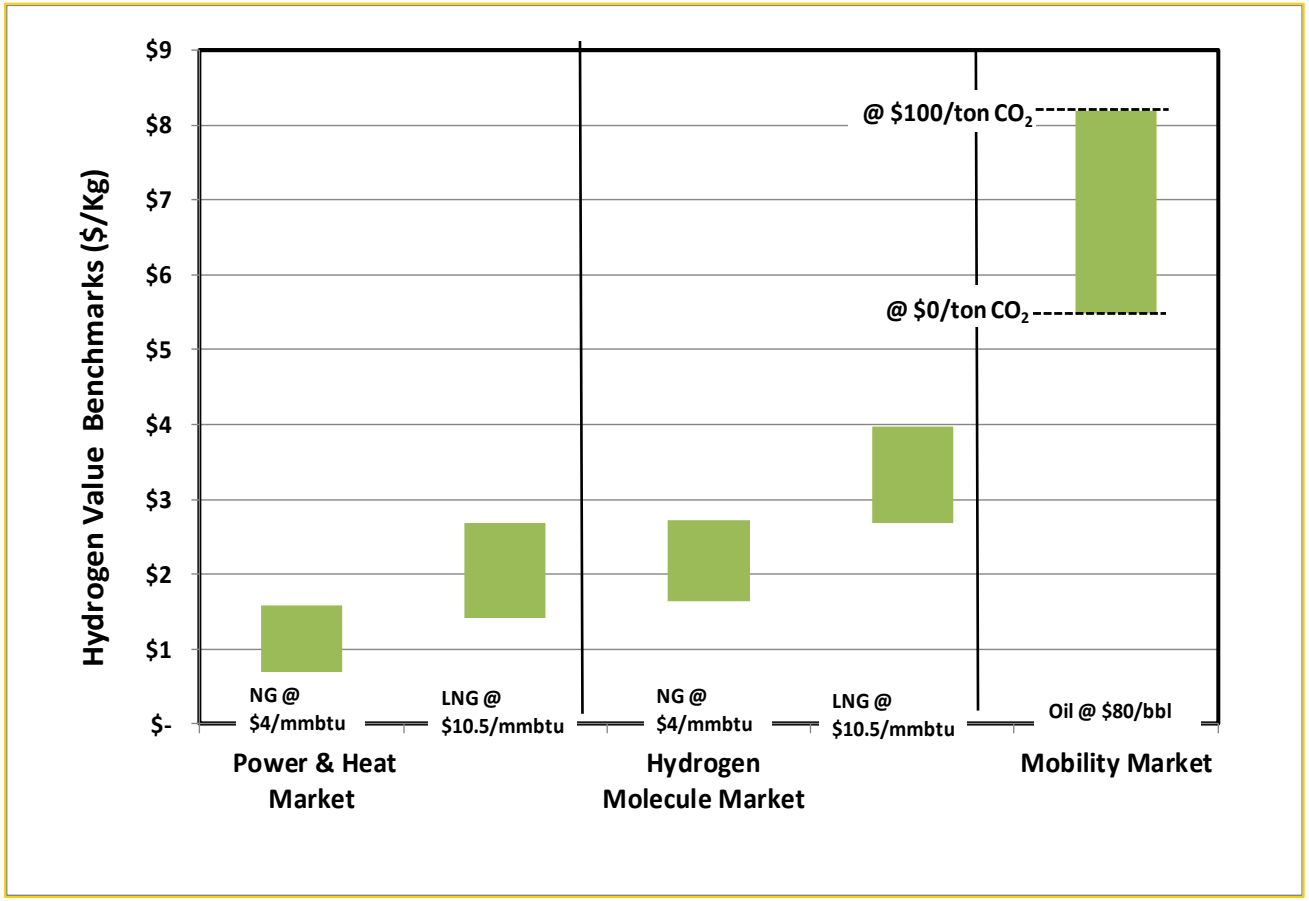
Unique CVP

- High efficiency
- Higher range than BeV (500 vs. 250km)
- Easily blended in gas turbine
- No need for CCS at plant
- Only real clean fuel solution
- Distributed power/heat, limiting electricity grid investments
- Clean
- High efficiency

H2 MOBILITY'S UNIQUE CVP AND A PREMIUM OUTLET

- Hydrogen Fuel Cell Electric has a clear range advantage, but Battery Electric is improving fast…



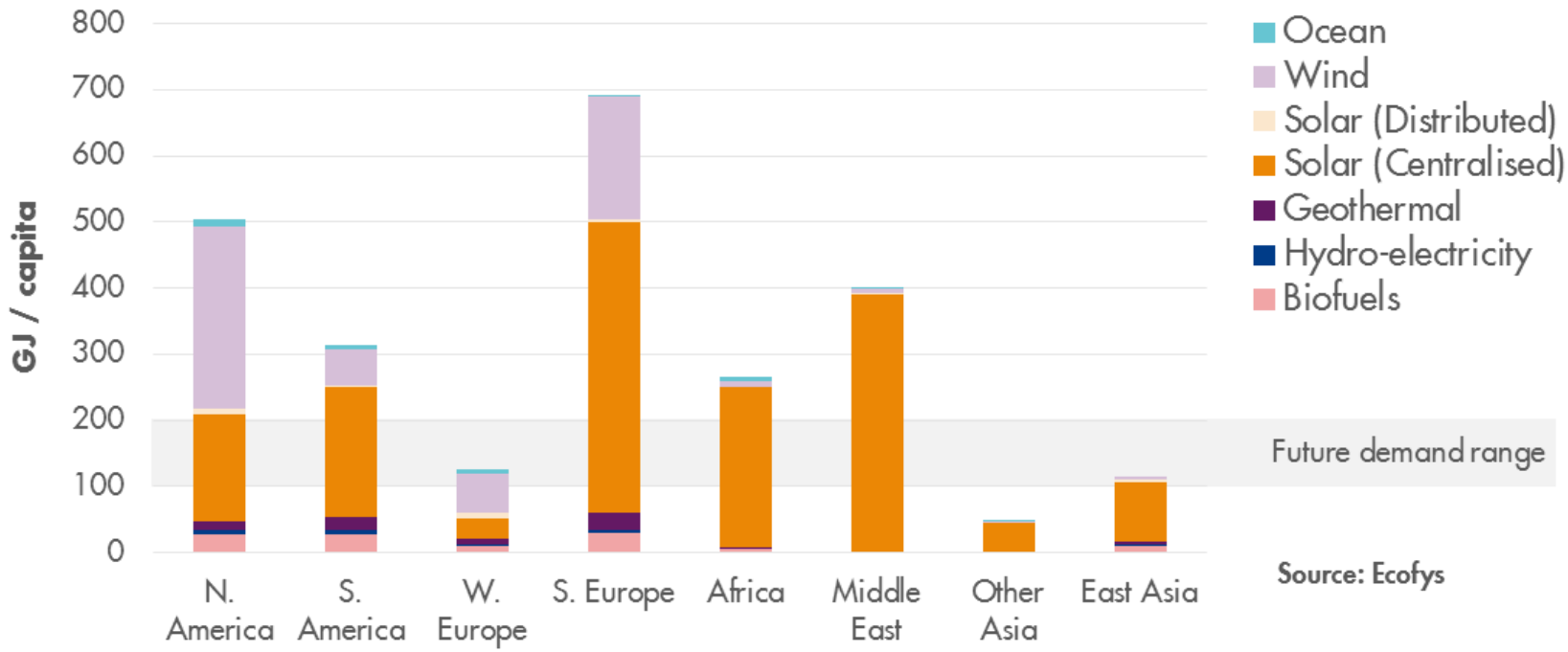


* "A portfolio of power-trains for Europe: a fact-based analysis (2010)", McKinsey & Industry coalition

* Shell Analysis

Future Energy Transport: LH2

Import needs future energies

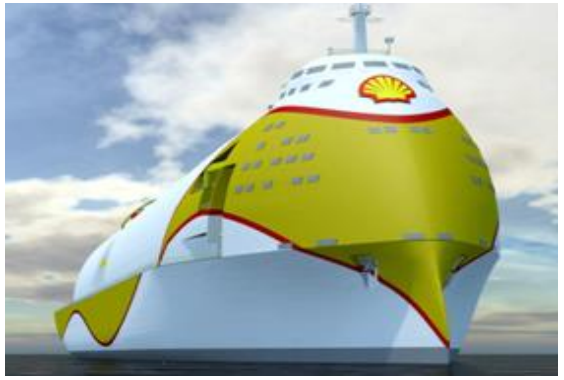


Source: Ecofys

Kawasaki

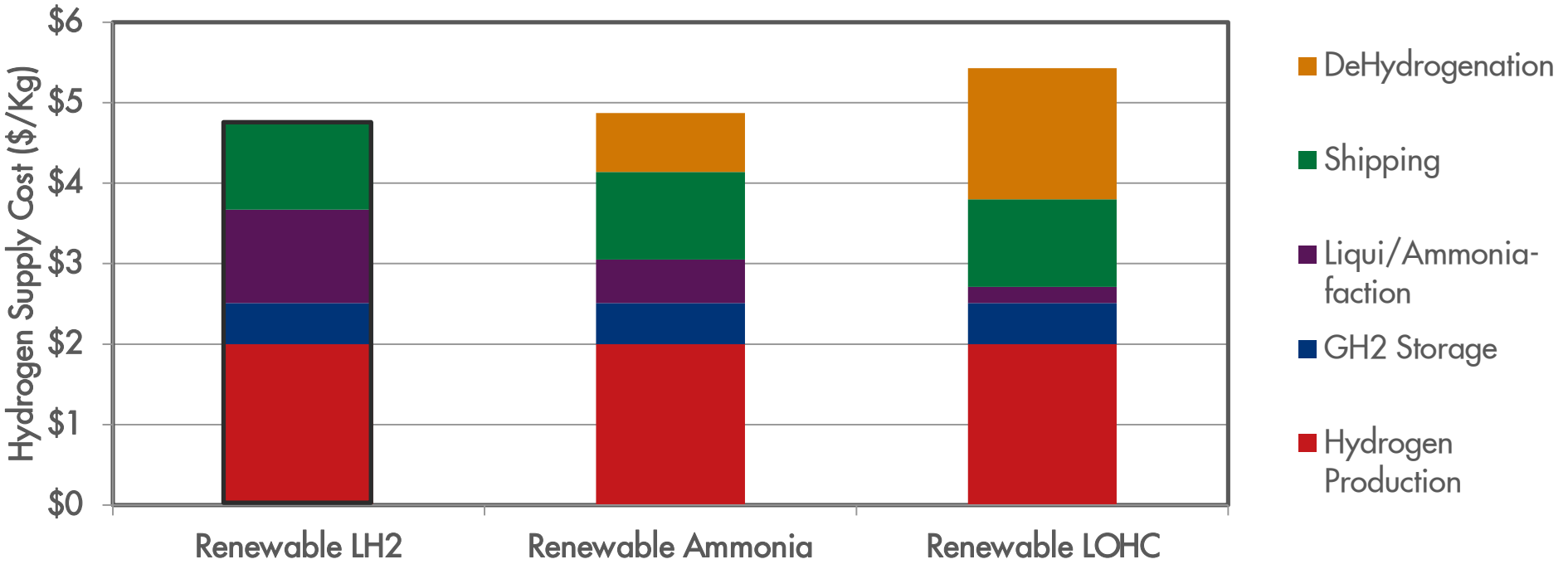
Iwatani

J-POWER



LH2 AN ATTRACTIVE OPTION FOR H2 TRANSPORT & STORAGE

Supply Chain: Green/Clean Prod (Middle East)→ H2 → Storage → NH3/LH2/LOHC → Shipping (Cargo as fuel) → H2



Dehydrogenation energy "loss" gives away all the upstream advantages for NH3 & LOHC

Notes:

1. Production from NG + CCS or from large scale electrolysis using renewable energy, at a future *assumed* costsof 2 $/kg
2. Shipping costs similar for Ammonia, LOHC and LH2 as dominated by fuel costs (lighter cargo & high ship speed for LH2)
3. Dehydrogenation represents thermodynamic energy loss due to cracking, and is applicable also for the cases of direct use applications

BUT MANY CHALLENGES TO BE SOLVED IN SUPPLY CHAIN

H_2 Liquefaction

	Capital Intensity ($M/TPD)	Energy Loss
Reference (LNG)	$0.3	10%
Incumbent	$0.7	30%
Aspired (new cycle)	$0.5	15%

- **Bigger cold box & novel turbo machinery** design for ultra-low temp & large scale production
- **New refrigerants (He/Ne cycle) & efficient catalysis** for ortho/para conversion

Bulk LH_2 Shipping

	Capital Cost ($MM)	Cargo (mT)	Cargo (mTLNG equiv)	Daily boiloff
Reference (QMAX)	$300 - $350	120,000	120,000	0.1%
Aspired Design	$400	20,000	60,000	0.4%

- **Cargo containment systems** to serve **extreme Cryogenics & minimize boil-off product loss** via H_2 **propulsion**
- **Safe operation** of **loading, transit & offloading**
- LH_2 **Standards & Regulation**

H2 Utilization (Demand)

- H2 **Mobility** – Significant **Retail Infrastructure CAPEX** & Complexity
- H2 **Power** - H2/NG blend turbines (0 -100%)
- H2 **Industry** – Supply Infrastructure
- H2 **Buildings** – Supply Infrastructure & Systems development needed
- H2 **Aviation/Marine** – Reliability, testing

Most importantly, demand needs to be created in all these sectors globally so supply chain development investments can deliver on promise.